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Final Report

Contract Number: FA9550-04-1-0196
Title: Slow Light in Semiconductor Quantum Well Waveguides

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Key words: slow light, fast light, electro-magnetically induced transparency

1. Abstract

The main objective of the program is to investigate various physical phenomena and device structures that can lead to potential applications to all optical storage and processing. The physical effects include electro-magnetically induced transparency (EIT), coherent population oscillation (CPO) in semiconductor quantum wells (QW) or dots.

We carried out experimental implementation of EIT from electron spin coherence in a GaAs quantum well waveguide for the first time. We designed and fabricated the waveguide structure. We also designed and fabricated a miniature waveguide coupler attached to a cold finger in an optical cryostat. The EIT experiment using double-V energy configuration was carried out for the first time on a (110) QW waveguide. An absorption dip of ~10% indicates a slow down factor of 1000 was obtained with a spectral width ~ 1GHz at 4K. From the spectral width, the spin coherence lifetime can be inferred to be ~1 ns at 4K. We carried out frequency-resolved measurements of electron spin coherence lifetime from the measured EIT spectral linewidth. An asymmetry in the resonance lineshape was observed. All results will be critical for understanding the physical properties of (110) QW waveguide and implementation of optical delay lines for signal processing.

1.1 EIT in 110 GaAs QW Waveguide

We proposed a novel double-V energy configuration to achieve electromagnetically induced transparency (EIT) in semiconductors [1-2], leveraging the use of long electron spin coherence reported on (110) GaAs quantum wells (QW) [3-5]. Preliminary data was reported using (100) GaAs QWs at 50K [1]. Here, we report EIT signatures in a single GaAs QW waveguide grown on a (110) GaAs substrate. The electron spin coherence lifetimes were inferred from the EIT transparency window under various operating conditions, including temperature, pump power, and wavelength. This measurement is in contrast to previous spin lifetime measurements using pulsed excitation. We also show an anomalous EIT lineshape dependence on wavelength.

Our technique for measuring spin coherence is based on Ref. [1], where electron spin population is induced and measured optically with continuous-wave (CW) lasers. This is in contrast to previous work relying on pulsed excitation [3-5], which does not allow for wavelength resolution. We use a CW pump-probe configuration to induce spin coherence at the degenerate wavelength. The pump is a single frequency Ti:Sapphire ring laser and the probe is external cavity tunable diode laser. The two beams collinearly couple into the GaAs QW waveguide. Our sample is a GaAs(130Å)/$Al_{0.3}Ga_{0.7}As$ single QW slab waveguide, ~150 μm long, grown by MBE on an undoped (110) substrate. The photoluminescence (PL) linewidth is very narrow ~2 meV at 10K, indicating excellent quality. The differential transmission (ΔT) is measured via lock-in detection. The pump wavelength is tuned within the light hole (LH) QW absorption peak and the detuning between the probe and pump is scanned over a few GHz. Near zero detuning there is a peak in ΔT, attributed to EIT arising from long electron spin coherence.

The coherence resonance arises when the strong pump beam (TM polarized) couples a valence (LH) state to a conduction state of definite spin while the weak probe beam (TE polarized) couples the same valence state to a conduction state of opposite spin. The transition between the two conduction states is not dipole-allowed, forming a “V” EIT system in which the pump field and the coherence of the “dark” transition inhibit probe absorption. The coherence between the conduction band states is the electron spin coherence lifetime and as such the coherence lifetime can be calculated from the linewidth of the induced transparency. We characterize ΔT as a function of pump power and wavelength. The ΔT first increases with pump power until reaching a maximum and then reduces slowly, as predicted by theoretical calculations. A maximum ΔT/T of 10.2% was obtained at 7.6 mW pump power at 40K.

Figure 1 shows such peaks in ΔT, plotted at various temperatures for 5 mW pump power. As the temperature is increased from 4.2 K to 100 K, the linewidth of the resonance remains roughly constant, with the corresponding spin coherence time ~200 ps, as shown in Figure 2. This value is comparable to other reported low-temperature spin measurements, but does not increase as $T^{0.6}$ above 20 K as in Ref [3]. We note that sample variation may play a large role in both the τ_s value and behavior [3,4], and that the temperature dependence of the n-doped sample of Ref. [3] is somewhat similar to our measurements.

The dependence of spin coherence lifetime on pump power is shown in Figure 3. We measure a monotonic decrease of τ_s with increasing excitation power, following the trend of Ref. [3]. As temperature is increased, the dependence on pump power weakens. At 4.2 K the dependence is roughly $I^{-2/3}$, at 20 K ~ $I^{-1/2}$, and at 40 K ~ $I^{-1/3}$. This trend is qualitatively in agreement with that reported in [3].

1.1.1 References

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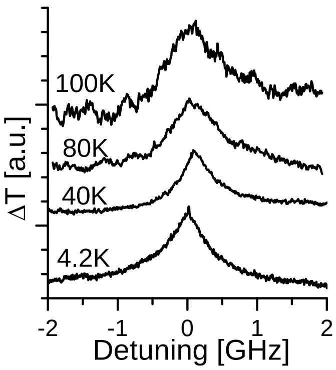

Fig. 1. Differential transmission at various temperatures (5 mW pump power). Scans were taken between 0.5 and 1 nm below LH line center

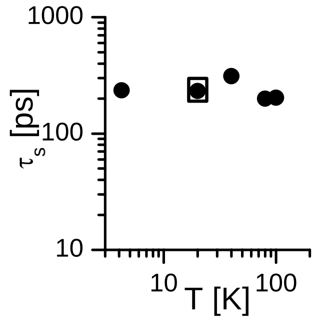

Fig 2. Spin lifetime vs temperature. For all points pump intensity I=5 mW except at 20K (square) where I=6.6 mW.

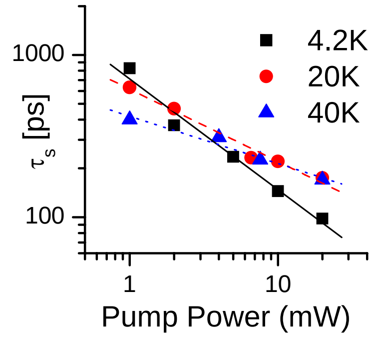

Fig. 3. Spin lifetime vs pump power for different temperatures. At 4.2 K the dependence is roughly $I^{-2/3}$, at 20 K ~ $I^{-1/2}$, and at 40 K ~ $I^{-1/3}$.

1.2 Optical Injection Locking of VCSEL

Using ultra-strong optical injection technique, we achieved DBP=1 for a high-speed modulated signal, with the highest speed obtained being ~14 GHz. The optical group velocity of a laser cavity (herein slave laser) is strongly effected by its threshold gain. Under injection locking, i.e. when the slave laser is subjected to the injection of a strong CW light source, the slave laser's lasing wavelength is pinned by the master laser. Due to the stimulated emission from the master laser, the gain required by the slave laser is greatly reduced in value. Thus, the carrier density is reduced, which red-shifts the slave cavity (due to a non-zero linewidth enhancement factor or alpha-parameter).

In our novel experiment, two room-temperature 1.55 μm VCSELs were used as the master and slave lasers. We modulate the master laser with a single-tone sinusoidal signal, creating two side bands. The optical carrier frequency acts as the CW mater line that locks the slave laser wavelength and shifts its cavity spectrum. The side bands thus experience different phases, resulting in a time advance or delay of the sinusoidal signal. Total delay as much as 2π is achieved for modulation frequency up to 14 GHz, as shown in Fig. 4. Tunable delay can be achieved by changing the detuning or drive current. This is the highest DBP*bandwidth product achieved.

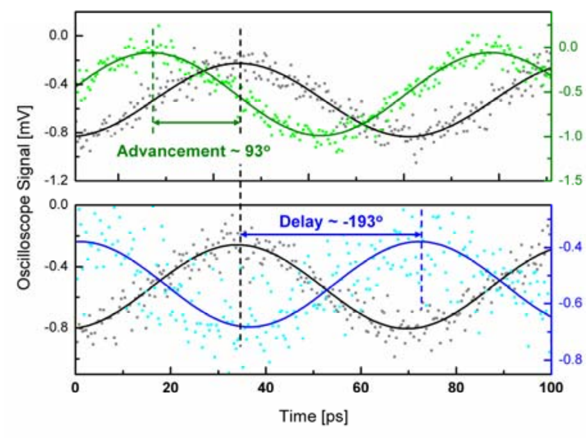

Fig. 4 Tunable delay/advancement of 2π for a 14 GHz signal using optical injection locked VCSEL.

1.3 Four-wave Mixing in a Self-Pumped Grating SOA

We recently demonstrated slow light achieved in an SOA with DBP~0.75 using an induced gain/index change due to the interaction of a pump, probe and the gain medium, e.g. via four-wave mixing in SOA. Mostly recently, we modified the approach to include two counter propagating optical pump beams and an optical grating. The optical grating allows us to work at the edge of the stop-band to increase the delay. The counter propagating beam enables us to achieve a uniform slow-down factor along the cavity to minimize propagation dispersion.

We realized the approach using a DFB laser as a self-pumped grating SOA. The probe laser, modulated by a single-tone sinusoidal signal at 2GHz, is coupled into the DFB SOA. Since the DFB lases at its stop-band edge, at which a fast phase change occurs, this can increase the delay or advancement of the modulation signal. We achieved a DBP=1 or phase change of 2π (Fig. 5). Continuous tunable delays are obtained by changing the detuning or drive current.

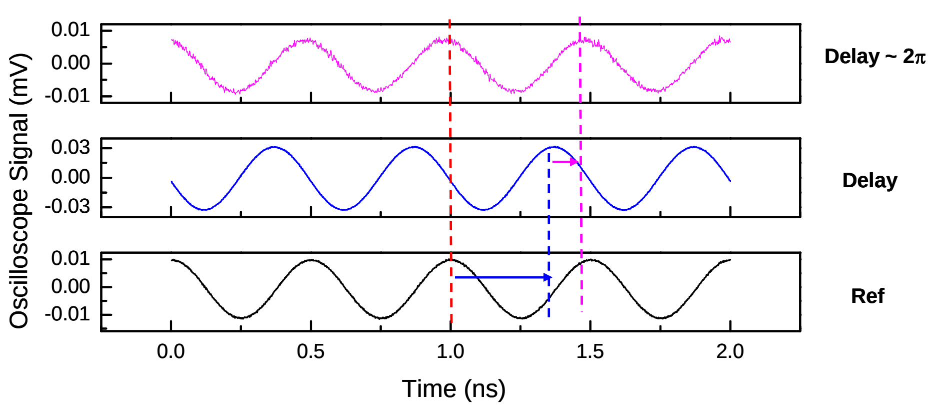

Fig. 5 Delay of 2π on a 2 GHz sinusoidal signal. Tunable delay is achieved by varying the wavelength detuning between pump and probe.

2. Personnel Supported:

1. Phedon Palinginis, Pei-Cheng Ku, post-doc, UC Berkeley (9/1/04- 7/1/05)

2. Susanta Sarkar, graduate student, Univ. of Oregon
3. Su-Wei Chang, graduate student, Univ. of Illinois, Urbana-Champaign

3. Publications:

1. Phedon Palinginis, Forrest Sedgwick, S. Crankshaw, Eui-tae Kim, Michael Moewe, Connie J. Chang-Hasnain, Hailin Wang, and Shun-Lien Chuang, "Ultra Slow Light (< 200 m/s) Propagation in a Semiconductor Nanostructure", Applied Physics Letters, 87 (17), Art. No. 171102, OCT 24, 2005
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7. Uskov AV, Chang-Hasnain C, "Slow and superluminal light in semiconductor optical amplifiers", ELECTRONICS LETTERS 41 (16): 922-924 AUG 4 2005

4. Interactions/Transitions:

4.1 Participation/presentations at meetings, conferences, seminars, etc.

1. Xiaoxue Zhao, Phedon Palinginis, Bala Pesala, Connie J. Chang-Hasnain, Philip Hemmer, "Tunable Ultraslow Light in 1550 nm VCSEL Amplifier", ECOC postdeadline paper, Glasgow, UK 2005.
2. Phedon Palinginis, Forrest Sedgwick, S. Crankshaw, Eui-tae Kim, Michael Moewe, Connie J. Chang-Hasnain, Hailin Wang, and Shun-Lien Chuang, "Ultra Slow Light (< 200 m/s) Propagation in a Semiconductor Nanostructure", CLEO postdeadline paper, May 2005.
3. Susanta K. Sarkar, Phedon Palinginis, Hailin Wang, Pei-Cheng Ku, Connie J. Chang-Hasnain, N. H. Kwong and R. Binder, "Inducing electron spin coherence in GaAs quantum well waveguides: Spin Coherence without spin precession" QELS May 2005.
4. Susanta Sarkar, Phedon Palinginis, and Hailin Wang, Pei-Cheng Ku and Connie J. Chang-Hasnain, N.H. Kwong and R. Binder, "Inducing electron spin coherence without magnetic fields in GaAs quantum well waveguides", APS Annual Meeting March 2005
5. SHU-WEI CHANG, SHUN-LIEN CHUANG, University of Illinois at Urbana-Champaign, CONNIE J. CHANG-HASNAIN, University of California at Berkeley, HAILIN WANG, "Slow Light Using Electromagnetically Induced Transparency from Spin Coherence in [110] Strained Quantum Wells", APS Annual Meeting, March 2005

6. Pei-Cheng Ku, and Constance J. Chang-Hasnain, Rodney S. Tucker, "Link Performance of All-Optical Buffers Using Slow Light", Optical Fiber Communications Conference Technical Digest. Anaheim, CA, 6-11 March, 2005.
7. Lukas Chrostowski, Xiaoxue Zhao and Connie J. Chang-Hasnain, Robert Shau, Markus Ortsiefer and Markus-Christian Amann, "50 GHz Directly-Modulated Injection-Locked 1.55 μm VCSELs", Optical Fiber Communications Conference Technical Digest. Anaheim, CA, 6-11 March, 2005.
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4.2 Consultative and advisory functions to other laboratories and agencies, especially Air Force and other DoD laboratories. Provide factual information about the subject matter, institutions, locations, dates, and name(s) of principal individuals involved.

None

4.3 Transitions.

None

5. New discoveries, inventions, or patent disclosures. (If none, report None.)

None

6. Honors/Awards:

None